APPARATUS FOR MEASUREMENT OF ELECTRON-GAMMA DIRECTIONAL CORRELATIONS

by

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B. S., Kansas State University, 1962

A MASTER'S THESIS

submitted in partial fulfillment for the

requirements for the degree

MASTER OF SCIENCE

Department of Physics

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1965

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TABLE OF CONTENTS

Introduction

The measurement of the directional correlation between the radiations emitted in a two step cascade transition between three nuclear energy levels is useful in determining certain properties of the radiations and of the nuclear energy states themselves.

In a two step cascade transition there is often a directional correlation between the first and second radiations emitted in a given cascade. Nevertheless, the total directional distribution of the radiation in laboratory coordinates is isotropic if the radioactive sample does not lie in a strong external magnetic or electric field so that the nuclei are randomly oriented.

The directional correlation may be observed without external fields by the use of two separate detectors. The outputs of the two detectors are connected to separate single channel analysers (Fig.1), one of which is set to accept the first radiation while the other is set to accept only the second radiation. The outputs of the single channel analysers are fed to a fast coincidence circuit and a scaler is used to count the number of coincidences. One detector is fixed while the other may be rotated about an axis through the radioactive sample, and the coincidence rate

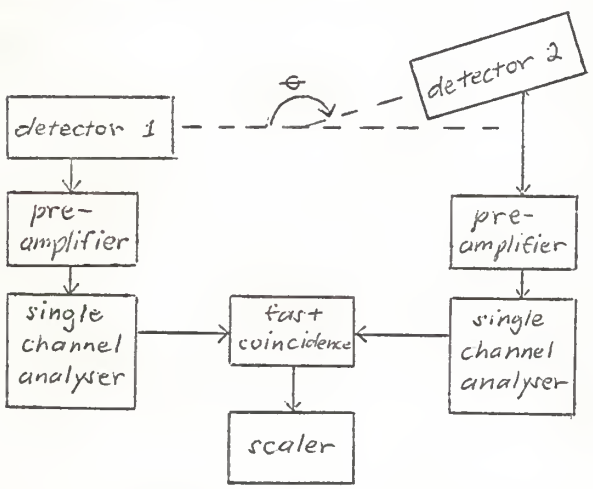


Fig. 1 - Simple schematic drawing of apparatus for directional correlation measurements.

is recorded as a function of the angle θ.

After certain corrections are applied the data thus gathered give the angular distribution of the second radiation with respect to the first.

Theoretical equations have been derived which give the angular distribution as a function of the type of radiation and of various nuclear parameters. These equations are given in Appendices I and II for several types of cascades along with an explanation of the physical processes involved and a simplified derivation.

Apparatus

The primary purpose of the apparatus constructed is to measure electron-gamma directional correlations using a solid-state detector for conversion electrons and a NaI (Tl) scintillator crystal detector for gamma rays. The solid-state detector is chosen for its very high energy resolution, while the scintillation detector is chosen for its high efficiency in the detection of gamma rays. Solid-state Germanium gamma ray detectors have much higher resolution than scintillation detectors but much lower efficiency for the detection of the higher energy gamma rays.

In addition, to ensure the highest resolution it is necessary that the silicon solid-state detector be cooled to temperatures as low or lower than that of a solution of dry ice in acetone. With some solid-state detectors it is imperative that no moisture or other contaminants condense on the sensitive surface. This is especially true for the surface barrier type as the gold electrode on the sensitive surface is not impervious to the passage of large molecules. For this reason and to avoid electron scattering in the air and in the layer of moisture that would otherwise condense on the cold detector, it is necessary to surround the detector and the radioactive sample with vacuum or with a light, dry gas such as pure hydrogen.

A secondary consideration influencing the design of the apparatus is that it be adaptable to as many different types of experiment in nuclear spectroscopy as possible, including the recording of singles spectra using cooled solid-state detectors. In all cases it is desirable to keep the intensity of the scattered radiation in the vicinity of the detectors as low as possible.

In order to measure the background for a given spectrum an absorber must be provided that can be inserted or removed without disturbing the detectors or the radioactive sample. This absorber is also used in determining the spurious coincidences that form the background in an electron-gamma coincidence experiment. In making a determination of a background the absorber is placed between the electron detector and the sample to eliminate all electrons coming directly from the sample, but allowing most of the gamma rays and scattered electrons to reach the electron detector. The background count is then subtracted from the count rate without an absorber to obtain the true coincidences or singles spectra.

The first design considered was patterned after alpha-gamma directional correlation apparatus designed by W. C. Cobb (Ref. 1). In this design a solid-state alpha detector is fixed inside a cylindrical brass vacuum chamber, $4\frac{1}{2}$ inches high by 4 inches in diameter, which also contains the radioactive sample. No cooling for the solid-state detector is provided. A window, one sixteenth inch thick, for the passage of the gamma rays is machined into the wall of the chamber. A major disadvantage of this design is the attenuation and scattering of the gamma rays due to the interference of the window. Also the intensity of scattered radiation within the chamber is high due to its small size and the high atomic number of the brass walls.

To overcome these disadvantages a large aluminum vacuum chamber was constructed to enclose both detectors. The chamber has inside dimensions 20 inches wide by $23\frac{1}{2}$ inches long by 8 inches high and is shown in Plates I, II, and IV. The low Z material and large size act together to reduce the intensity of the scattered radiation within the chamber. To reduce further the intensity of the scattered radiation, the chamber

is lined with one-quarter inch thick lucite which, due to its low average atomic number, predominantly absorbs rather than scatters electrons.

The solid-state detector is fixed to the end of an arm which is in direct contact with a resevoir of coolant, while the scintillation detector is mounted on an arm which pivots about an axis through the radioactive sample which remains fixed. The arm can be manipulated from outside the chamber and the angle θ between the solid-state and scintillation detectors can be varied from 70 to 180 degrees. There is a large removable plexiglass window through which the source and both detectors can easily be observed along with a scale indicating the angular position of the scintillation detector. A similar angle scale is also provided outside the chamber. The window is removable and doubles as an access port to the interior of the chamber. The pumping system consists of a fore pump with a liquid nitrogen cold trap inserted in the vacuum line between it and the chamber. There is also a cold trap in the chamber. The entire apparatus is supported on a metal framework with the chamber above and the pump with its cold trap below.

The chamber itself is constructed from duraluminum plate one inch thick with the top and bottom plates grooved to receive the sides, which are also grooved to receive each other. The chamber is held together with one-half inch steel bolts, six on a side. The joints are sealed from outside with RTV 102 silicone rubber adhesive sealant. It is thus possible to take the chamber apart for cleaning or to make modifications simply by removing the bolts and breaking the seal. The old sealant can be scraped off and the new sealant can be applied after the chamber is reassembled. When the chamber is evacuated the maximum possible inward deflection at the center of the base plate is 1/64 inch as calculated from a formula given by Timoshenko (Ref. 2). The round window cum access port is made from $1\frac{1}{2}$ inches thick grade G plexiglass for which the maximum possible

deflection at the center was calculated to be 1/32 inch, also from a formula taken from Timoshenko.

An 'O' ring seal, Parker number 2-459, made from Parker compound number N525-6 is used to seal the access port. The 'O' ring is seated in a groove machined in the aluminum chamber to specifications given by the Parker Seal Company. The 'O' ring and groove are to be kept clean and lightly greased with high vacuum grease to protect the 'O' ring from damage and to avoid leakage. The window is held in place solely by air pressure and is provided with handles for easy removal. When replacing the window it should be reset in exactly the same position each time as the net force on the window is so great that an impression of the 'O' ring groove and imperfections in the top bearing face of the chamber is pressed into the lucite. For this reason markings are provided for location of the lucite window. As solid-state detectors must always be used in darkness to avoid breakdown, opaque taping is applied to the edges of the lucite window and a removable opaque cover is provided for its face.

The lucite lining inside the chamber is screwed to the aluminum walls with brass screws, each one of which has a small hole drilled axially through it to allow rapid evacuation of gases in the blind hole behind each screw. Spacer washers .040 inches thick are placed between the lucite lining and the walls, and one-eighth inch holes are drilled at three inch intervals in the lucite to facilitate the evacuation of gases trapped between the lining and the wall.

BNC bulkhead receptacles, number UG 657/U, are located at strategic points in the chamber wall to allow for wire leads to the detectors inside the chamber. Each receptacle is located in the center of an area, one and one quarter inches in diameter, in which the wall is reduced to

a thickness of $\frac{1}{4}$ inch. These receptacles are hermetically sealed internally and each seals to the chamber wall with a small 'O' ring. They are thus easily removable. A helium-leak-tested Hoke needle valve, Hoke number R308MN, is provided for the admission of air to the chamber. This valve has an orifice .070 inch in diameter,'O' ring packing and a nylon stem point.

The vacuum pump is a Cenco Hyvac 14 two stage pump with a guaranteed ultimate vacuum of .1 micron. Rubber vacuum tubing with an inside diameter of 5/8 inch is used to connect the pump to the chamber. Inserted in this line is a liquid nitrogen trap (Plate V C) for trapping oil and other vapors. The trap is immersed in a Dewar flask of 7 cm.inside diameter filled with liquid nitrogen. A curve of the amount of liquid nitrogen evaporated from the flask versus time is shown in Plate VIII. A thermocouple vacuum gauge is screwed directly into the chamber wall.

To give the system a high pumping speed for water vapor and to provide extra protection from the condensation of vapors on the cold solid-state detector, a second cold trap is placed in the chamber itself fairly close to the solid-state detector (Plates I and II). Section drawings of the two types of trap that have been built for this purpose are shown in Plate V. Both types are essentially glass Dewar flasks at the bottom of which a tube, closed at one end, protrudes into the chamber. Each flask has a 50/50 standard taper male ground-glass seal integrated into the lower end. These seals mate with a female tapered seal machined from aluminum and glued into the wall of the chamber with Devcon metal-filled epoxy resin glue. Thus the Dewar flasks are easily removable from the chamber. If they have not been removed from the chamber for several weeks the flasks may stick but they can be freed by heating the aluminum seal for several minutes with a 200-300 watt soldering iron. When replacing

a flask it is essential that both seals be clean and free from grit and lightly greased with high vacuum grease.

One type of Dewar flask (Plate V B) relies solely on the vacuum within the chamber to provide insulation between its inside and outside walls, while the upper part of the other type (Plate V A) is permanently evacuated to a pressure of 10^{-5} mm Hg between the double walls. In this type a bellows is included in the inner wall to keep the flask from breaking when coolant is added to it. The bellows stretches to allow the inside wall to contract in length while the outside wall stays constant. Both types are completely silvered between the walls to minimize heat transfer by radiation.

Several flasks of each type have been constructed. Some are provided with all-glass tubes on the lower end. These are used as cold-traps. Others are provided with Kovar metal-to-glass seals one inch in diameter and closed on the metal end. The solid-state detector is fastened to a mount that is clamped to the metal end of one of these seals. (Plate VI D).

The solid-state detector mount is shown in Plates I; II; III A,B, C,D; IV). The horizontal arm on which the detector is mounted is retractible or extendable by loosening the four lower knurled nuts and sliding the arm in or out. Arms of two different lengths are provided so that the distance between the detector and the source can be adjusted continuously from zero to about 12 centimeters. A threaded hole is drilled in the end of the arm into which some of the detectors may be screwed directly. In addition, several adapters are provided that can be screwed into the hole, thus allowing several other kinds of solid-state detectors to be mounted on the arm. The arm is leveled by means of an adjusting screw and is then locked in position by tightening lock nuts on the rear

pivot and the adjusting screw. As Kovar has a very low temperature coefficient of expansion, the part of the mount that clamps to the Kovar is made from copper which also has a fairly low temperature coeffient of expansion. The rest of the mount is made from brass for ease of manufacture.

The scintillation detector mount is shown in Plates I-IV. The detector is mounted on an aluminum carriage which slides in grooves on a movable aluminum arm covered with three-eighths inch thick lucite. The pivot for the arm consists of a smooth cylindrical brass rod, three quarters of an inch in diameter, fixed perpendicularly to the underside of the arm. This rod passes through a tightly fitted hole in the lucite lining and thence through an 'O' ring seal to the outside of the chamber. A three-eighth inch hole is drilled at right angles through the part of the rod that protrudes outside the chamber. Through this hole is placed a rod which serves as a lever arm to rotate the scintillation detector. A Teflon bearing is placed between this rod and the 'O' ring housing, keeping the three-quarter inch rod from being forced up into the chamber when the chamber is evacuated. To remove the aluminum arm from the chamber the lever rod can be removed and the 'O' ring housing loosened, after which it is possible to lift the arm straight up and out of the chamber. As the lucite can scratch the three-quarter inch rod when it is pulled out, special care should be taken to pull straight up so as not to apply any torque to the arm about a horizontal axis. The rod and the 'O' ring seal should be kept greased with high vacuum grease at all times.

The scintillation detector is removable from its carriage by loosening the screws on the rear support and sliding the entire detector assembly out toward the back. The magnetic shield for the photomultiplier

tube (Plate III E) is held in place by the front support. It is not advisable to remove the magnetic shield unless absolutely necessary because it may be damaged by rough handling.

The photomultiplier tube is inserted directly into a diheptal tube base which contains the voltage divider to provide the proper dynode potentials. An emitter follower is fastened directly to the tube base. The anode of the photomultiplier tube is connected to the input of the emitter follower through a high voltage coupling capacitor. A complete schematic circuit diagram of the voltage divider and the emitter follower is shown in Plate VI. The entire voltage divider and the high voltage connections are encased in Dow-Corning Sylgard Dielectric potting compound, primarily as a safety factor since no arcing or corona discharge can occur within the chamber as long as the pressure within the chamber is kept below about twenty microns. This holds for the maximum voltage that can be applied to the anode at the photomultiplier tube, 1300 volts. However, arcing can occur at higher pressures if the high-voltage components are not all well insulated. At pressures of about 300 microns arcing has been observed to occur right through the insulation on the high-voltage lead if it is brought near a corner of metal. It is thus not advisable to apply the high voltage until a pressure of twenty microns or less has been reached.

Two scales are provided to determine the angular position of the scintillation detector with respect to the solid-state detector. The first scale is inscribed inside the chamber on the lucite lining covering the floor. A pointer visible in Plate III F is fixed to the aluminum arm, and is adjustable for length to allow zeroing of the angle scale. The second scale located outside the chamber, shown in Plates I and II A, is used to adjust the angular position of the scintillation detector without letting light into the chamber, and is read from a

pointer on the brass lever arm. This scale has no markings. The inside scale is first zeroed after which it is used to calibrate the outside scale. Pencil marks are placed on the outside scale at the angular positions at which it is desired to measure the coincidence rate when performing a directional correlation experiment. The most commonly used positions are 90°, 120°, 150° and 180°.

The radioactive source is fixed on the end of a short lucite rod, (Plates I, II and IV) inserted into a hole drilled axially into the brass rod that acts as the pivot for the scintillation detector. The lucite rod is prevented from turning when the scintillation detector is rotated by a one-eighth inch aluminum rod inserted through the base of the lucite rod and into the chamber wall. The source is made by depositing and then evaporating a drop of a solution of radioactive material on the center of a thin metal foil or Nu-Skin film stretched across a hole in a small aluminum plate. The aluminum plate screws to the lucite rod. The adjustment of the height of the source and its exact location over the pivot point of the scintillation detector is accomplished mainly by the careful placement of the liquid drop on the foil or film. A template is useful for this purpose. The distance from the center of the source to the top of the arm on which the scintillation detector is mounted should be exactly 8.48 centimeters.

A movable absorber is provided within the chamber (Plates I and II C) in which standard graded aluminum or lead absorbers can be mounted on a lucite arm which is fixed on the end of an aluminum rod, one-quarter inch in diameter. This rod passes out through the chamber wall in an arrangement similar to that used with the three-quarter inch rod forming the pivot for the scintillation detector mount. The absorber

can thus be manipulated from outside the chamber to any position between the source and the solid-state detector or it can be retracted. Once located, the absorber is clamped in position by a wooden clamp on the aluminum rod outside the chamber. Wood is used to avoid scratching the rod. The rod should always be kept clean and greased with high vacuum grease, and great care should be taken to avoid scratching it. If it is necessary to remove the rod it can be pulled out toward the inside of the chamber after loosening the 'O' ring housing.

The exact adjustment of the location of the solid-state detector with respect to the radioactive source must be made before directional correlation measurements are made. Before making the following adjustments the radioactive source should be removed from the chamber. The first step is the preliminary leveling of the arm to which the detector is mounted by means of an adjusting screw. (See Plate III A). A vernier caliper is used to ascertain when the arm is parallel to the top of the arm on which the scintillation detector is mounted. Then the height of the solid-state detector is adjusted to exactly 8.48 centimeters above the top of the scintillation detector arm by sliding the detector mount up and down on the metal-to-glass seal and finally clamping it in position. The level of the arm is then rechecked. If it is not level the procedure described above is repeated. After the adjustments have been completed, the arm to which the solid-state detector is mounted is extended to its full length until the detector almost touches the lucite rod which supports the radioactive source. The detector isthen horizontally centered on the rod by rotating the Dewar flask to which it is attached. Then one sights vertically downward to the arm on which the solid-state detector is mounted and rotates the scintillation detector until lines

inscribed on the top of the scintillation detector arm parallel to its axis are parallel to the solid-state detector arm. The pointer for the scale inscribed on the chamber floor is then adjusted so that the scale reads 180 degrees. The solid-state detector is finally retracted to the desired distance from the source and locked in position, completing the adjustments required.

Whenever air is admitted to the chamber the surfaces of the cold traps that are exposed inside the chamber should be warmed up, cleaned and dried before closing the chamber and starting the pump again. It is best to use the large peranently evacuated type of Dewar flask as the upper trap for the chamber as, even when this type of flask is full of liquid nitrogen, moisture condenses only on the lower part from which it is easily removed. Water can condense between the inside and outside walls of the non-permanently evacuated type. This water is very hard to remove and it can damage the silvering. Immediately after admitting air to the chamber, the flask serving as the upper cold trap should be removed, emptied and left upside down. This prevents frost from forming inside it. If frost forms in the flask and then melts, the water that collects can cause breakage when the flask is subsequently refilled with coolant. Any frost that forms in the flask should be removed by rinsing the flask with acetone. Water should not be used since it is difficult to completely empty the flask because of the trapping of the liquid in the bellows.

A curve of pressure versus time for the evacuation of the chamber after it has been open to the atmosphere for about a half-hour is shown in Plate VII. Before taking this data the chamber had been evacuated for four days but had been open for several days before that. (More rapid evacuation is possible if the chamber has been open for only a few

hours in the preceding week or so.) The time of evacuation is longer if the chamber has been left open for a day, due to the adsorption of gases by the parts within the chamber. The trap for the pump can be refilled as soon as one minute after the pump is started and should be filled not later than fifteen minutes after starting the pump.

If the chamber has not been open for more than a few hours in the preceding week, at any time after a pressure of 50 microns is reached the filling of the upper cold trap has the immediate effect of lowering the pressure to one-tenth of a micron in five minutes or less. If this trap is filled when the pressure is 100 microns or less, a pressure of about three microns is reached very quickly, after which it takes about half an hour to reach one micron or less. If the chamber has been open for several days a pressure of three microns will be reached very quickly after filling the upper trap, when the pressure in the chamber is fifty microns, but as much as twelve hours may be required to reach one micron. The sooner the upper trap is filled the more moisture condenses on the tube protruding in the chamber. Moisture continues to condense on the trap at a slow rate as long as the trap is kept filled. However, if a detector is cooled with a solution of dry ice in acetone, the moisture does not condense on it, only as long as the upper trap is kept filled with liquid nitrogen. It is thought that this moisture is given off by the parts within the chamber, because the amount of moisture collected by the traps is greatly increased if the chamber is left open for a few days before evacuating the chamber. It has happened that oil has condensed on the detector mount when it was cooled with a solution of dry ice and acetone even though the upper trap was filled with liquid nitrogen. It is thought that this was due to the level of liquid nitrogen in the lower trap falling below the level at which the trap

was still effective. It appears that after the lower trap is filled the level of nitrogen should not be allowed to fall below four or five inches below the top of the Dewar flask in which the trap is immersed. This level is reached six hours after filling it. For greater protection against vapors given off by the pump it would be advisable to construct a larger and more effective trap for the pump, one which would remain effective for at least ten hours after filling. The condensation can also be greatly reduced by using better pump oil.

As it is not necessary to cool solid state electron detectors to liquid nitrogen temperatures, a solution of dry ice in acetone is sufficient. To avoid condensation of water vapor the cool solid state detectors must be warmed to room temperature before the chamber may be opened. This is done by pumping the dry ice-acetone solution from the flask and adding warm acetone. The acetone is then pumped out and hot water added, after which one must wait about one hour before opening the chamber. For use with a dry ice-acetone solution the non-permanently evacuated type of Dewar flask is superior to the permanently evacuated type as it is easier to remove the solution from it, and there is no danger of condensation of moisture between its walls. One of these flasks with the bare detector mount attached one-third full of acetone and two-thirds full of crushed dry ice will last at least fourteen hours before more dry ice must be added.

If it is desired to use a solid-state germanium gamma ray detector which must operate at the temperature of liquid nitrogen, it is best to use the large permanently evacuated flasks. As these detectors must be kept cool even when not in use it is necessary to open the chamber without first warming them up. This is possible since the RCA type is not injured by condensation of vapors on its surface.

A bonus in the design of this chamber is the possibility of doing electron-gamma and gamma-gamma coincidence experiments using two cooled solid-state detectors. This can be done by replacing the upper Dewar flask that serves as a cold trap by a flask with a Kovar metal-to-glass seal on its lower end on which the second detector is then mounted.

Curves showing the rate of evaporation of liquid nitrogen from the Dewar flasks with various attachments inside the chamber are shown in Plates IX and X. While obtaining these curves an aluminum foil cap was placed over the top of each flask as shown in Plate II, A and B. This prevents ice from forming in and around the tops of the flasks and reduces evaporation. A major contribution to the rate of evaporation arises from the radiant heat absorbed by the parts projecting into the chamber. This can be seen by comparing the first and second curves in Plate IX. The first curve is for a non-permanently evacuated flask with the bare detector mount attached while the second is for the identical case except that the detector mount is wrapped in aluminum foil. Because the absorptivity of aluminum foil is much lower than that of tarnished brass and copper the consumption of liquid nitrogen due to the parts projecting into the chamber is reduced from 190 cc/hr to 110 cc/hr. The rate of evaporation due to heat absorbed by these parts was determined by taking the slope of the evaporation curve at the point where the flask is almost empty.

From Plates IX and X it appears that the rate of evaporation from the permanently evacuated flasks is slightly lower than that for the non-permanently evacuated type. The average consumption over the time interval from full to empty for the permanently evacuated type with the foil wrapped detector mount attached is 120 cc/hr, while that for the non-permanently evacuated type with the same attachment is 140 cc/hr.

Some discrepancy in the measurements exists since the measured consumption due to heat absorbed by the parts of the flasks located below the tapered seal is 100 cc/hr for the permenently evacuated type and 110 cc/hr for the non-permanently evacuated type, even though both had the same attachments within the chamber. However, these values are close enough to be attributed to experimental error. The error is possibly due to the fact that even though the vacuum was the same, the chamber was more thoroughly out-gassed when the experiment was performed on the permanently evacuated type so that fewer vapors condensed on the foil wrapping the detector mount. The better performance of the permanent type is partly due to the larger size since both types have a large rate of consumption just after filling, 120 cc in the first half hour. The average consumption for the period from one-half hour after filling to empty is 120 cc/hr and 130 cc/hr for the permanently and non-permanently evacuated types respectively with the foil wrapped detector mount attached. Since the total surface area of the permanently evacuated type is about twice that of the non-permanently evacuated types it is clear that the permanently evacuated type is more fully insulated in the upper part. The silvering is better since it is protected from moisture and the vacuum between the walls is higher. However, as previously stated, the non-permanently evacuated type is still best for mounting detectors to be cooled by a solution of dry ice and acetone.

The above measurements were all taken without a solid-state detector mounted on the detector mount so no wire leads were attached. The attachment of two fairly thin wire leads increases the consumption by a maximum of 10 cc/hr depending on the length and cross-section of the wires.

In order to test the apparatus the attempt was made to duplicate the results of Rao (Ref. 9) in the measurement of the directional correlation between the 358 Kev gamma ray and the K conversion electrons from the 81 Kev transition of Ba^{133}. This attempt was unsuccessful due to the aforementioned problem of the condensation of oil on the cold electron detectors and with instability in the energy scale of the gamma ray spectrum from the scintillation detector. The instability did not appear at first but developed as the experiment progressed. It was finally traced to faulty components in the emitter follower and has since been corrected.

In the experiment a scintillator crystal 1" thick by $1\frac{1}{2}$" in diameter was used to detect the gamma rays and an Ortec SBEE 100-500 detector was used to detect the conversion electrons. The source was made by depositing Ba^{133} on a Nu-Skin film. Plate II C shows the radioactive source and the detector in the same positions as those used in the experiments.

A 400 minute live time singles spectrum of Ba^{133} taken during the experiment is shown in Plate XI. Due to the instability of the emitter follower the resolution is poor.

The total electron spectrum in coincidence with the 358 Kev gamma-ray is shown with background subtracted in Plate XII.

Three types of spurious coincidence counts were subtracted from the measured coincidence rate to obtain the true coincidence rate. These were counts due to chance coincidences between the 358 Kev gamma-ray and electrons detected by the electron detector (chance e^-) and counts respectively due to true and chance coincidences between the 358 Kev gamma-ray and gamma-rays detected by the electron detector (true and

chance Compton). Other processes such as coincidences with scattered radiation were neglected.

In order to determine the background three coincidence runs were made. The first run was taken with a delay inserted in series with the output of one detector. This gave the sum of the chance e^- and chance Compton spectra. A second run was taken with no delays but with a 500 mg/cm^2 aluminum absorber inserted between the source and the electron detector to absorb the electrons but not the gamma-rays. This gave the sum of the true Compton and the chance Compton spectra. The third run was taken with both the delay and the absorber. This gave only the chance Compton spectrum. To obtain the total background the difference between the second and third spectra was added to the first spectrum.

For very precise coincidence measurements it would be advisable to exactly determine how great is the background due to scattered radiation. It is assumed that this background is quite low due to the low Z number of the Lucite lining and aluminum walls of the chamber.

The solution of the problem of oil condensation should make it possible to perform accurate electron-gamma directional measurements. In addition it will be possible to perform gamma-gamma, electron-gamma and electron-electron coincidence experiments with this apparatus using only solid-state detectors with their inherent high resolution.

Explanation of Plate I

Cutaway drawing of the vacuum chamber. Some of the small interior details such as the inside angle scale and the voltage receptacles have been omitted from the drawing. The scintillation detector is shown schematically as a rectangular box and is shown in the angular position 150°.

PLATE I

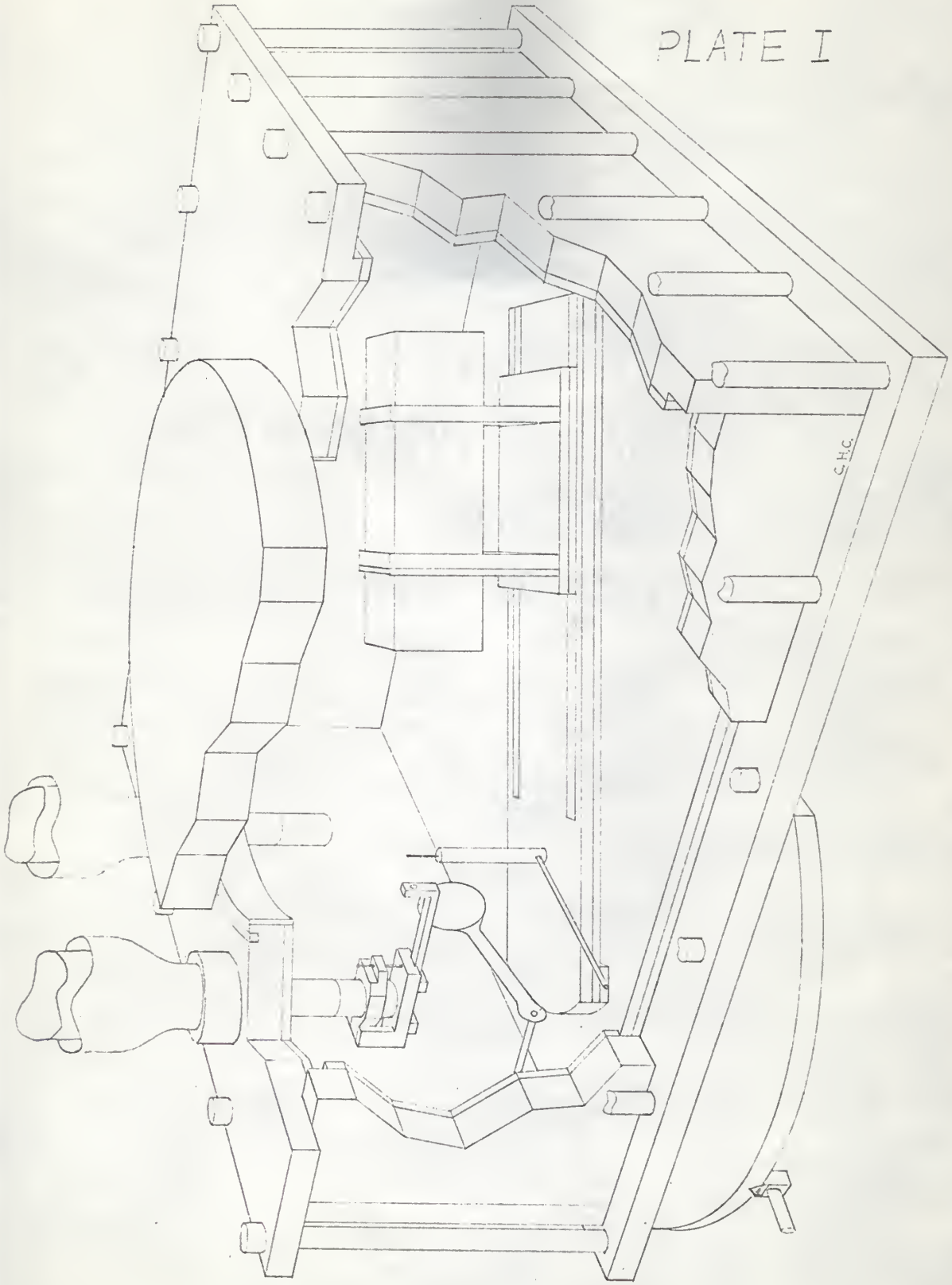
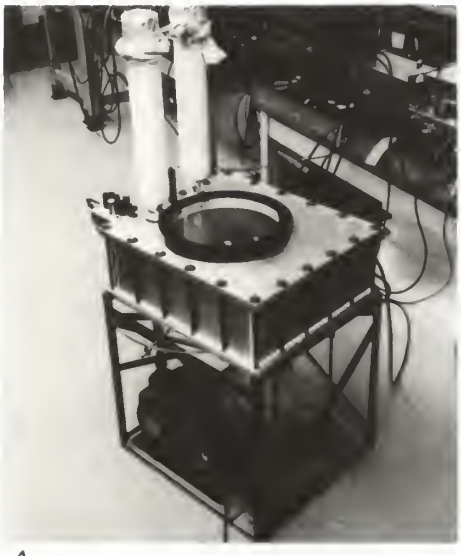


PLATE II

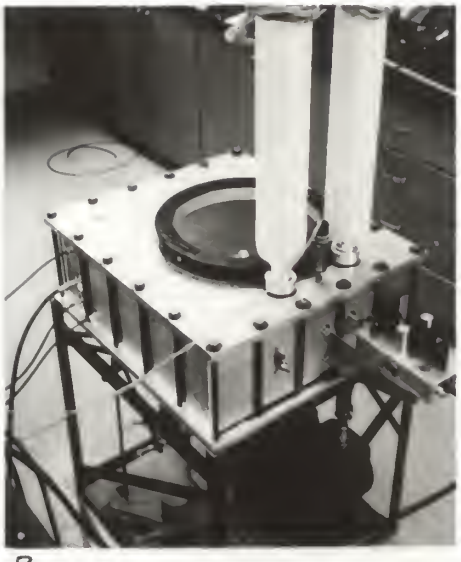
A and B Views of the entire apparatus in operation with the permanently evacuated Dewar flasks being used both as the upper cold trap and as the detector mount. The preamplifier for the solid-state detector is affixed directly to the side of the chamber by means of a bracket.

C View inside chamber with access port removed, and with scintillation detector in the 180^{o} position. A solid-state detector is in position along with a radioactive source and the non-permanently evacuated type of flask is being used as the detector mount. The absorber can be seen behind the source in a retracted position.

D Same as C but with the scintillation detector and mount removed and placed on top of the chamber.



A



B

C

D

PLATE II

PLATE III

A Side view of solid-state detector mount.

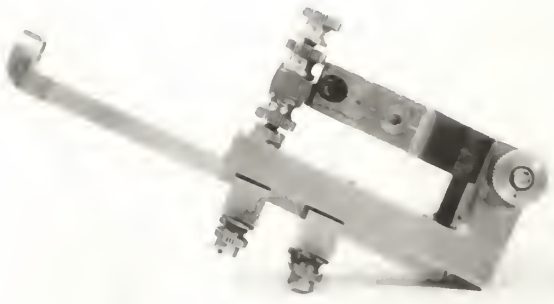
B Top view of the part of solid-state detector mount which fits on the Kovar tube.

C Bottom view of part of solid-state detector mount shown in B.

D Solid-state detector mount affixed to a non-permanently evacuated type flask.

E At left is the scintillation detector mount with the magnetic shield in place. At right is the scintillation detector itself consisting of NaI(Tl) crystal, photomultiplier tube and the emitter follower circuit, connected to the photomultiplier tube base at the right.

F The scintillation detector is affixed to its mount which is in place on the movable arm shown removed from the chamber, The pivot for the arm is visible at lower left, the inside scale pointer appears at lower right.



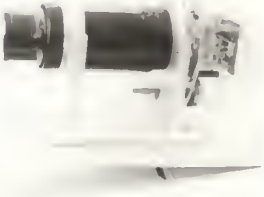
A

B

C

E

D



F

PLATE III

Explanation of Plate IV

Cross-sectional drawing of the vacuum chamber with the scintillation detector in the angular position 180°. The section is taken vertically through the axes of both detectors and the radioactive source. The drawing is one-quarter full size.

PLATE IV

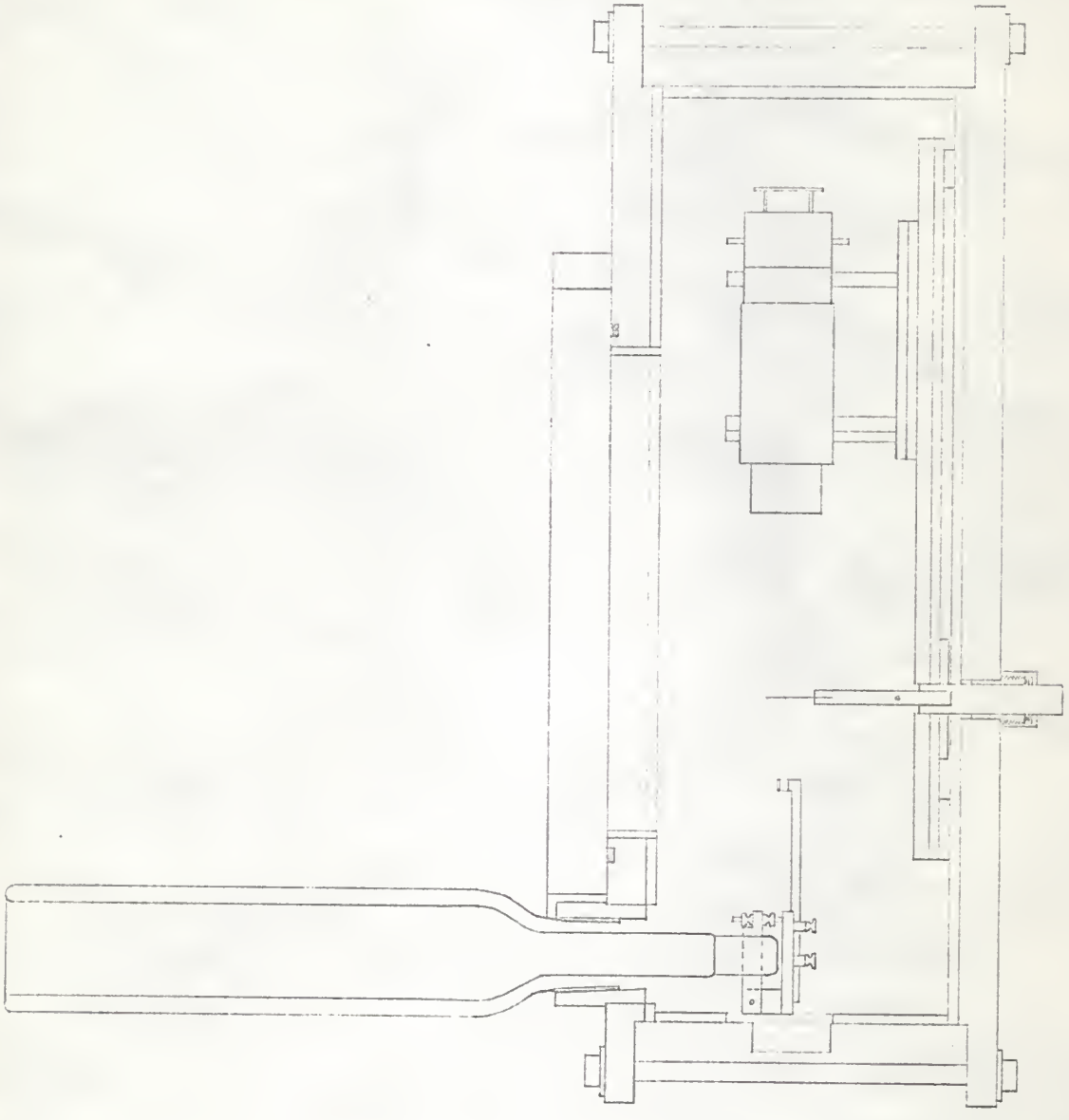


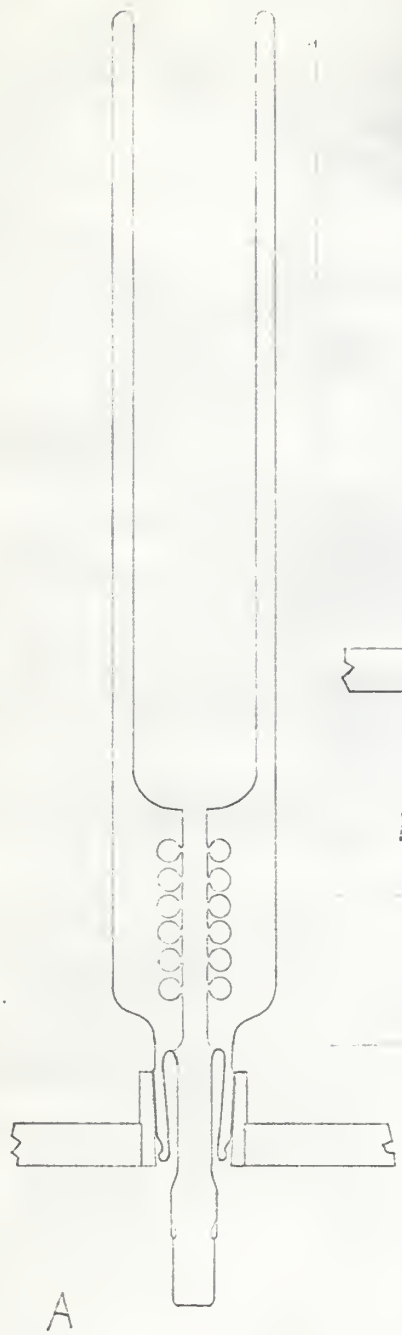
PLATE V

A Axial cross-section of the permanently evacuated type Dewar with a Kovar metal-to-glass seal forming its lower end. The flask is shown in place on the chamber.

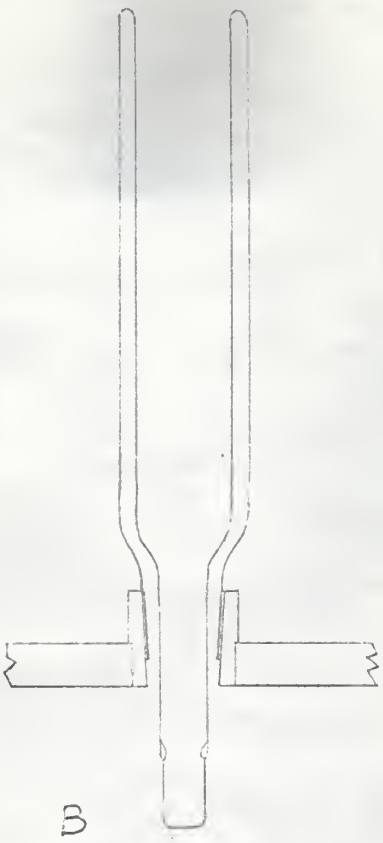
B Same as A except the flask is the non-permanently evacuated type.

C Axial cross-section of the lower liquid nitrogen trap for the pump.

PLATE V



A



B

C

Explanation of Plate VI

Schematic diagram of the voltage divider and emitter follower for the photomultiplier tube. The numbers 1 through 14 refer to connections to the pins of the tube.

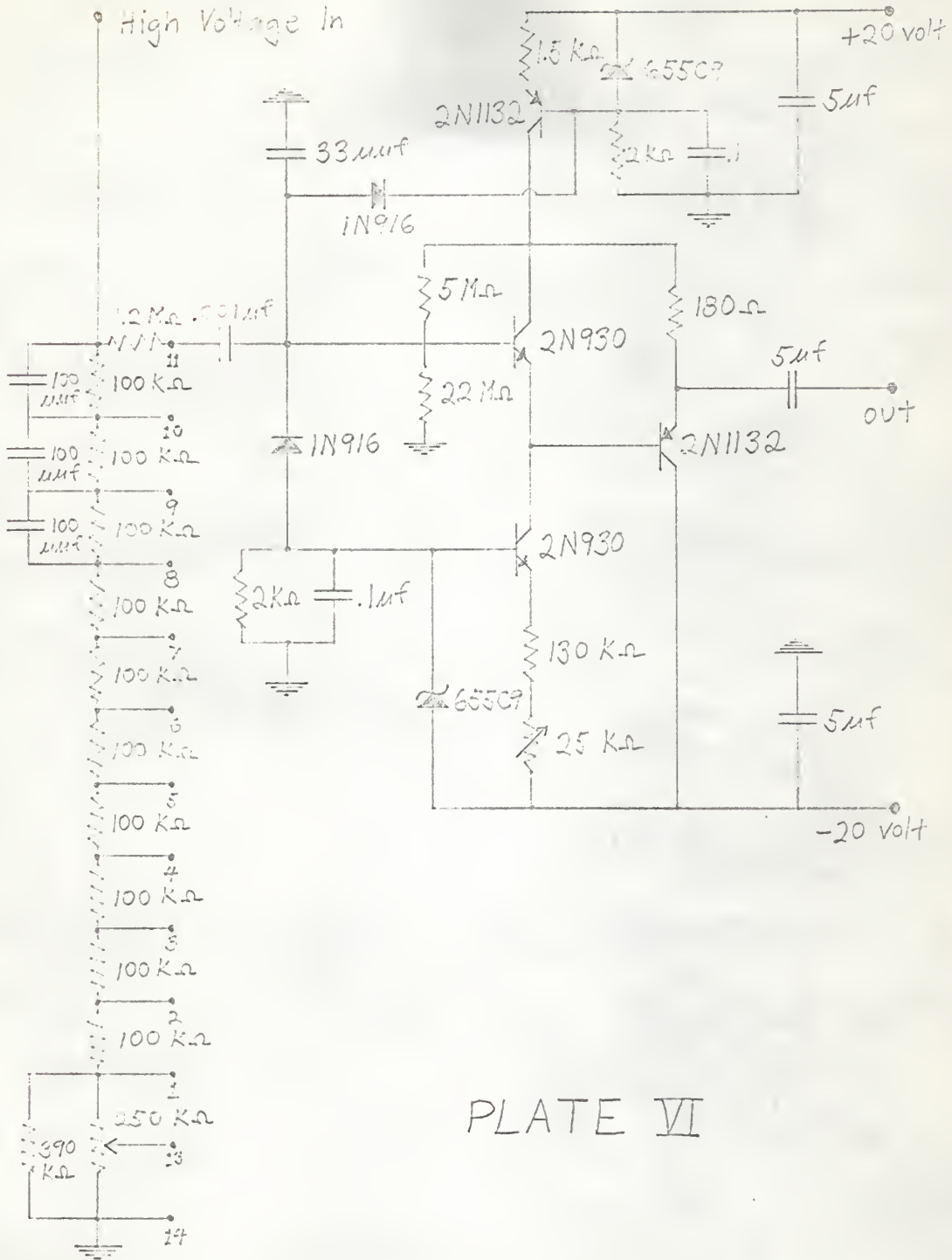
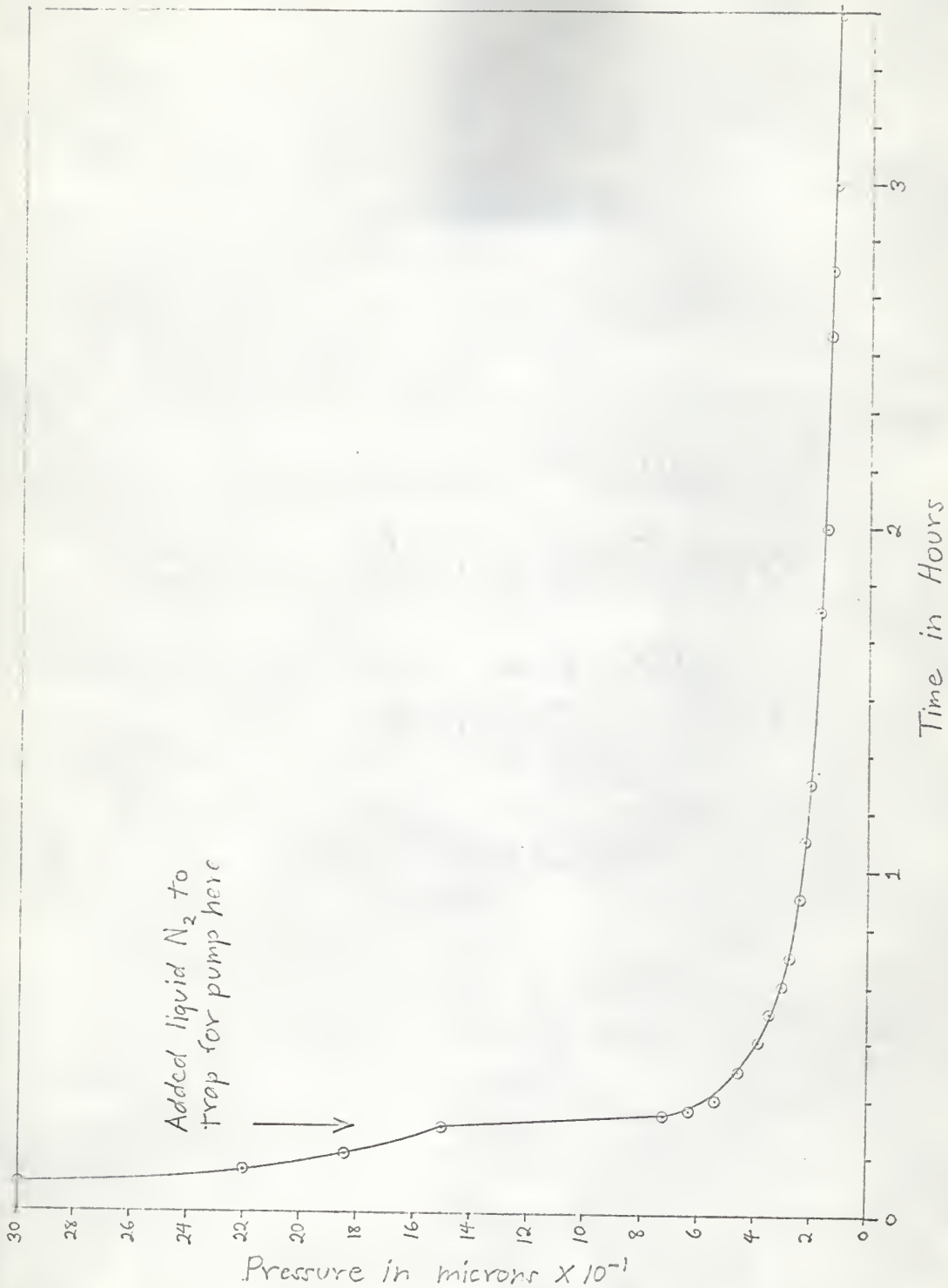

High Voltage In
+20 volt
1.5 KΩ
6550?
5μf
2N1132
33 μμf
2 KΩ
.1
1N916
5 MΩ
180Ω
2N930
5μf
out
.2 MΩ
.01μf
100 μμf
100 KΩ
22 MΩ
1N916
2N1132
2N930
2KΩ
.1μf
130 KΩ
6550?
25 KΩ
5μf
-20 volt
11
10
9
8
7
6
5
4
3
2
1
250 KΩ
390 KΩ
13
14

PLATE VI

Explanation of Plate VII

Curve of pressure versus time for the evacuation of the chamber with the upper trap warm. Before determining this curve the chamber had been open for a half-hour, before which it had been out-gassed for four days after being open for two days. The ultimate vacuum reached was six microns after seven hours. The speed of evacuation and the ultimate vacuum reached vary widely with the amount of out-gassing the chamber has undergone before being opened and with the time the chamber has been open immediately before evacuating. The pressure could have been reduced in a few minutes to one micron or less at any time greater than one-half hour after starting the pump, by filling the upper trap with liquid nitrogen.

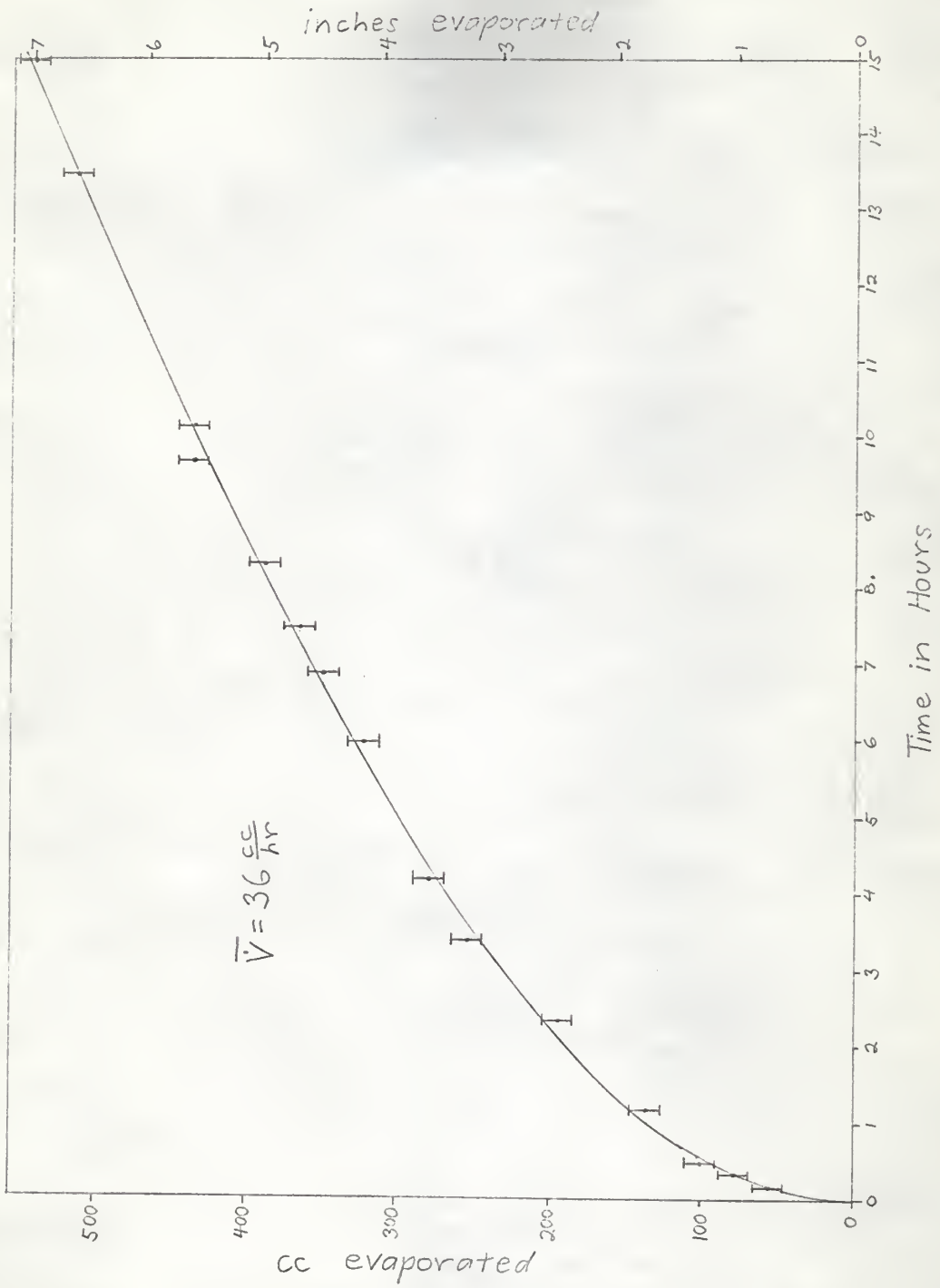
PLATE VII


Added liquid N_2 to trap for pump here
Pressure in microns X 10^{-1}
Time in Hours
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
1
2
3

Explanation of Plate VIII

Curve of amount of liquid nitrogen evaporated versus time from the Dewar flask in which the trap for the pump is immersed.
The average consumption over a fifteen hour period starting when the flask is full is 36 cc/hr. Before determining this curve the flask was allowed to attain thermal equilibrium when almost full. The flask was covered with aluminum foil during the test period.

PLATE VIII


inches evaporated
0
1
2
3
4
5
6
7
cc evaporated
0
100
200
300
400
500
Time in Hours
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
$\dot{V} = 36 \frac{cc}{hr}$

Explanation of Plate IX

Curve of amount of liquid nitrogen evaporated versus time from the non-permanently evacuated type of flask (Plate VB) with various parts inside the chamber:

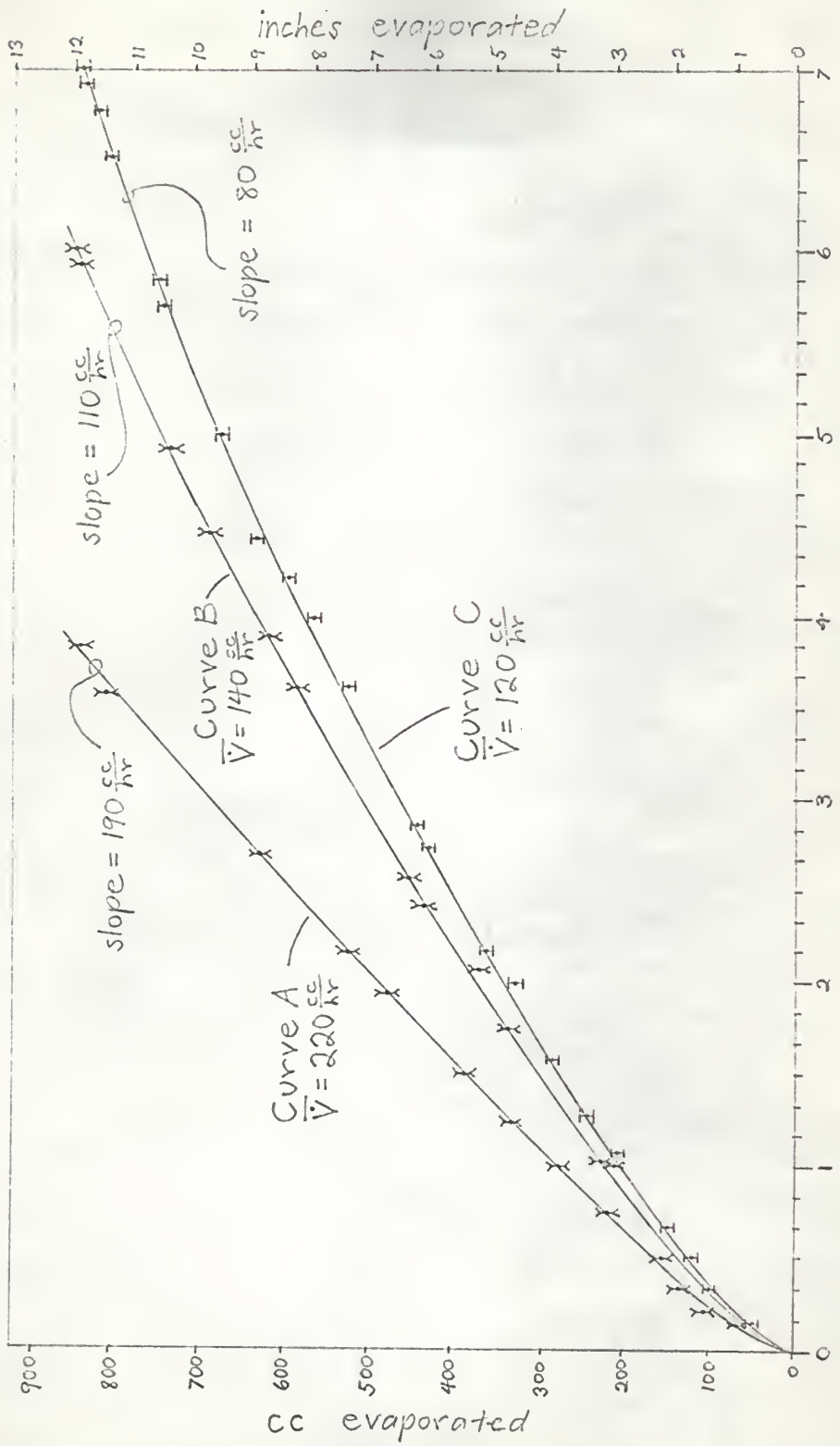
Curve A - bare solid-state detector mount attached to metal-to-glass seal, no wire leads attached.

Curve B - same as A except detector mount wrapped in aluminum foil.

Curve C - all glass closed tube $5\frac{1}{2}$ inches long by $\frac{1}{2}$ inch in diameter.

These curves were obtained in the same manner as that for the curve in Plate VIII.

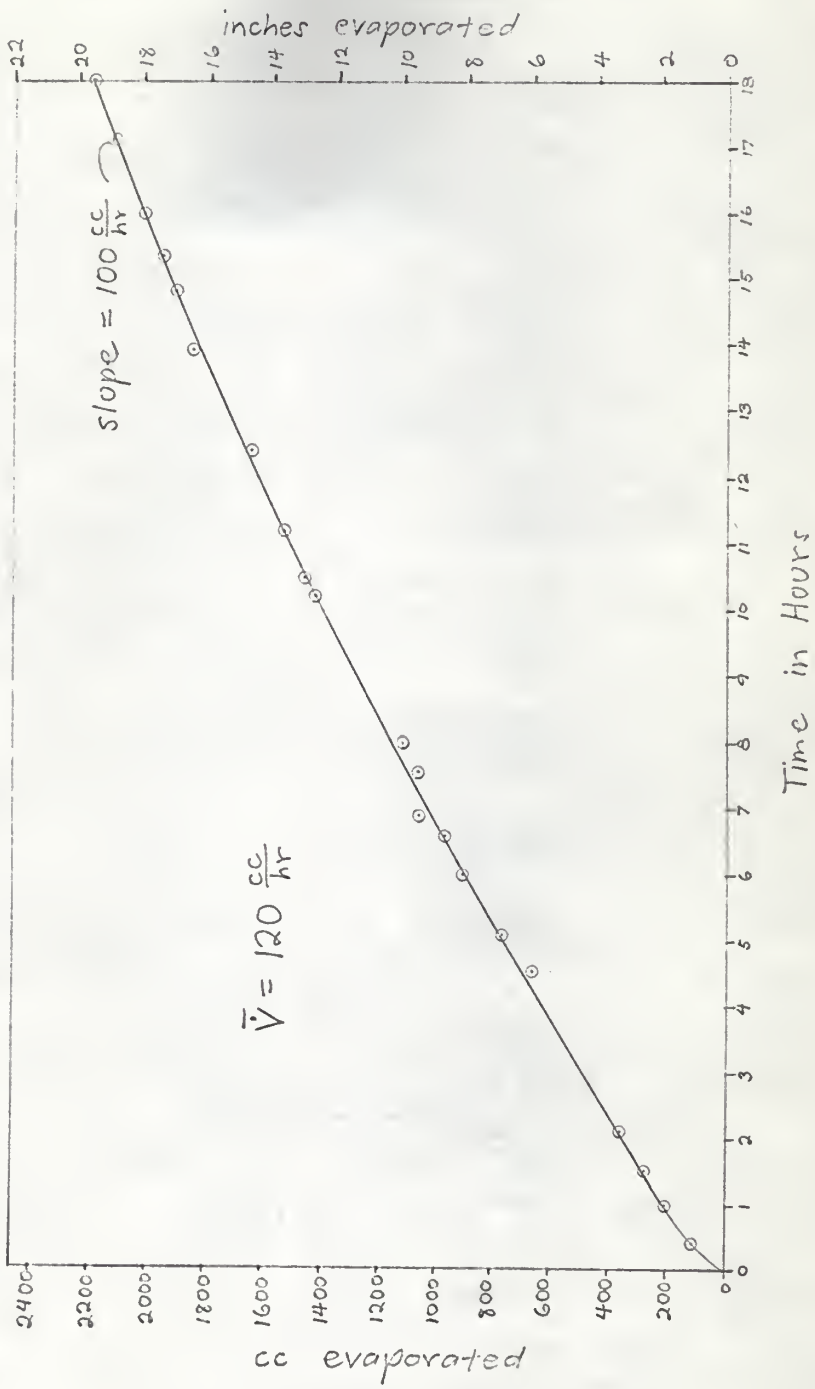
PLATE IX


inches evaporated
cc evaporated
Time in Hours
slope = 190 cc/hr
slope = 110 cc/hr
slope = 80 cc/hr
Curve A
V̇ = 220 cc/hr
Curve B
V̇ = 140 cc/hr
Curve C
V̇ = 120 cc/hr

Explanation of Plate X

Curve of amount of liquid nitrogen evaporated versus time from the permanently evacuated type of flask with two different parts attached inside the chamber. The same curve resulted for both attachments. The attachments were the aluminum foil-wrapped detector mount attached to a metal-to-glass seal, and a closed glass tube one inch in diameter and four inches long.
This curve was obtained in the same manner as that for the curve in Plate VIII.

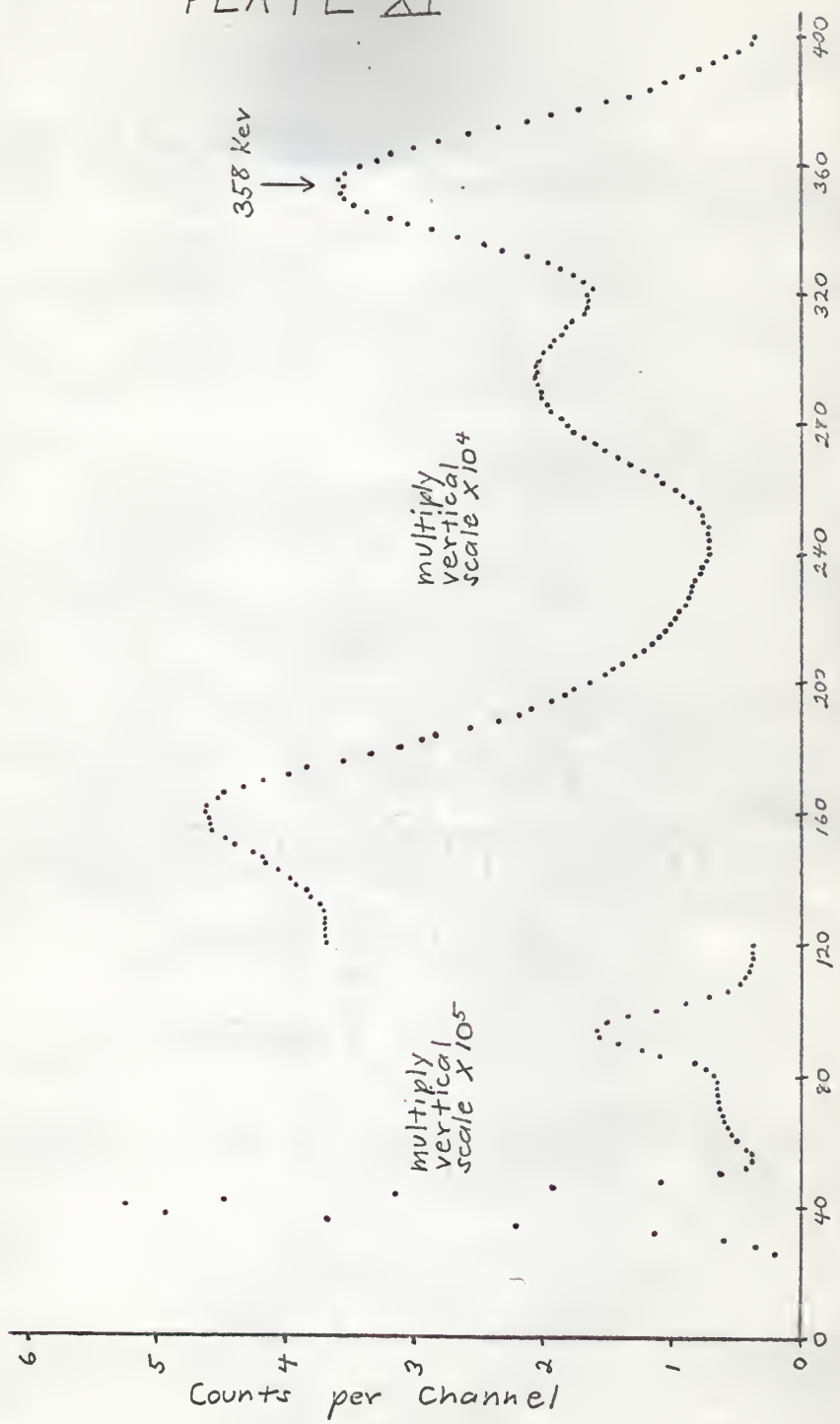
PLATE X


inches evaporated
22
20
18
16
14
12
10
8
6
4
2
0
slope = 100 cc/hr
$\bar{V}$ = 120 cc/hr
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
cc evaporated
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
Time in Hours

Explanation of Plate XI

Gamma-ray singles spectrum of Ba^{133}, taken with the arrangement shown in Plate II C. The pressure in the chamber was about 20 microns. The scintillation crystal was 1" thick by $1\frac{1}{2}$" in diameter.

PLATE XI


358 Kev
multiply vertical scale x10⁴
multiply vertical scale x10⁵
Counts per Channel
Channel Number
0
1
2
3
4
5
6
0
40
80
120
160
200
240
280
320
360
400

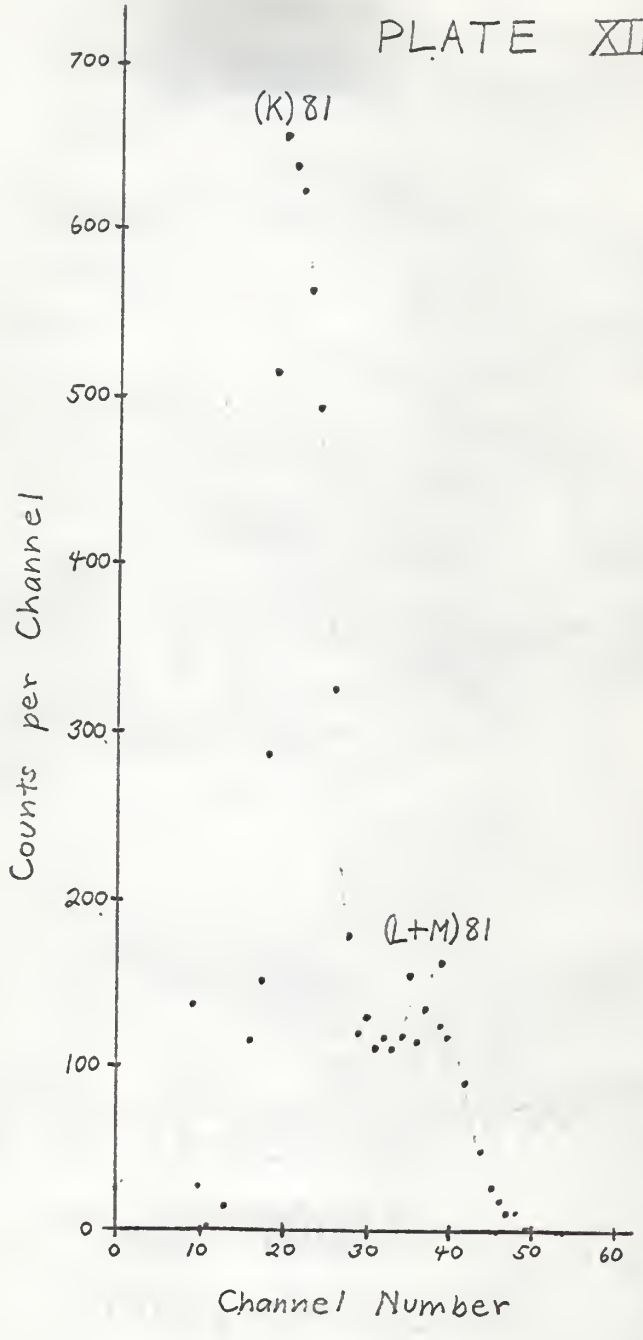
Explanation of Plate XII

Total spectrum of electrons coincident with the 358 gamma-ray of Ba^{133}, background subtracted. The live time is 400 minutes. An NaI (Tl) crystal 1" thick by $1\frac{1}{2}$" in diameter was used to detect the gamma-rays while an Ortec SBEE 100-500 detector was used to detect the electrons.

The arrangement shown in Plate II C was used. The pressure in the vacuum chamber was 1 micron and the electron detector was cooled by a solution of dry ice in acetone.

The counts in channels 0 through 10 are due primarily to noise. Peaks occur for the K conversion line and the combination of the L and M conversion lines of the 81 Kev transition.

PLATE XII


(K) 81
(L+M) 81
Counts per Channel
Channel Number
0
100
200
300
400
500
600
700
0
10
20
30
40
50
60

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(4) Preston, M. A.: "Physics of the Nucleus" Addison Wesley, Reading, Mass., 1962

(5) E. U. Condon and G. H. Shortley: "The Theory of Atomic Spectra" Cambridge, 1951

(6) L. C. Biedenharn and M. E. Rose: "Review of Modern Physics." V. 25 (1953), p. 729

(7) Rose, M. E.: "Physical Review," V 93 (1954), p. 477

(8) M. E. Rose, L. C. Biedenharn and G. P. Arfken: "Physical Review," V 85, #1 (1952) p. 5

(9) Rao, B. N. S.: "Nuclear Physics" U 27 (1951), p. 28-37

Appendix I

Theory of Gamma-Gamma Directional Correlation

In order to obtain a simple understanding of the process of directional correlation we will consider the naive theory of gamma-gamma directional correlation as developed by Frauenfelder. (Ref. 3)

The directional correlation between two successive radiations in a cascade $I_A \xrightarrow{R_1} I_B \xrightarrow{R_2} I_C$ arises because the directions of the first and second radiations are both related to the orientation of the angular momentum I_B of the intermediate level. This orientation is described by the magnetic quantum number M_B. For a correlation to exist I_B must not be zero and the lifetime of the intermediate state must be small enough so that the orientation does not change appreciably in a random fashion before the second radiation occurs.

The magnitude and orientation of the total angular momentum carried off from a given nucleus by a gamma ray is described by the angular momentum and magnetic quantum numbers L and M. M determines the projection of the angular momentum on an arbitrary Z axis. The angular distribution of a group of gamma rays all with identical L and M is proportional to the angular distribution of the radiation from an oscillating multipole of order L and orientation M.

This distribution is given by (Ref. 4):

$$S_L^M(\theta) = \left[2L(L+1)\right]^{-1}\left\{\left[L(L+1) - M(M+1)\right]\left|Y_L^{M+1}\right|^2 + \left[L(L+1) - M(M-1)\right]\left|Y_L^{M-1}\right|^2 + 2M^2\left|Y_L^{M}\right|^2\right\}$$

(equation 1)

The Y_L^M are the spherical harmonics and θ is the polar angle between the direction of the radiation and the Z axis.

If the magnetic substates of the level I_B are equally occupied the angular distribution of the radiation originating from that level is isotropic. That is $\sum_{M=-L}^{L} S_L^M(\theta)$ is equal to a constant.

The magnetic sublevels of a given level I_B in the entire group of nuclei in a radioactive sample are equally populated. However, in a directional correlation experiment detector two counts only those gamma rays that are immediately preceded by the detection of the first radiation in detector one. Thus the gamma rays counted are from a select group of nuclei. These nuclei do not have equally populated magnetic substates in the level I_B. This can be seen most easily if we choose a coordinate system with its axis along the line from the radioactive sample to detector one, that is in the direction of the first gamma ray. Henceforth all magnetic quantum numbers will refer to this special axis. The projection of the angular momentum of any photon on an axis parallel to its direction of motion is always $\pm\hbar$. Thus the magnetic quantum number of the first gamma ray is always ± 1. It is also possible to obtain this result from equation one. Unless $M=1$, S_L^M is zero for θ equal to zero. Therefore only radiation with $M=1$ can be detected by the first detector. The change in the magnetic quantum number of a nucleus upon emitting a gamma ray with magnetic quantum number M in making a transition from level A to level B with respective magnetic quantum numbers m_A, and m_B is given by $M=m_A-m_B$. Therefore the change in the magnetic quantum numbers of the nuclei in the select group when they undergo the transition $I_A \rightarrow I_B$ can only be ± 1. In a randomly selected group of nuclei the transitions to the intermediate level would exhibit all values of M for which $|M| \leq L$. Restricting the transition to $M=\pm 1$ causes the magnetic substates of the nuclei in the select group to be unequally populated.

In order to calculate the angular distribution $W(\theta)$ of the second gamma ray it is necessary to know the relative population $P(m_B)$ for each sublevel m_B and the relative transition probability $G(m_B, m_c)$ for each component $m_B \rightarrow m_c$, where m_c is the magnetic quantum number of the terminal level of the cascade. Then we may set

$$W(\theta) = \sum_{m_B} \sum_{m_c} P(m_B)\, G(m_B, m_c)\, S_{L_2}^{M_2}(\theta) \qquad \text{(equation 2)}$$

where L_2 and M_2 are the quantum numbers of the second gamma ray.

Note that since the second gamma ray can be emitted at any angle to the Z-axis the full range of magnetic quantum numbers may occur in that transition.

A quantum mechanical calculation shows that the relative transition probability is equal to the square of the Clebsch-Gordon coefficient for the vector addition $\underset{\sim}{I}_B = \underset{\sim}{I}_c + \underset{\sim}{L}_2$, $m_B = m_c + M_2$ (Ref. 3). The relative population $P(m_B)$ is given by the sum of all transitions $m_A \rightarrow m_B$ so that

$$P(m_B) \propto \sum_{m_A} G(m_A, m_B) \qquad \text{(equation 3)}$$

in which $m_B = m_A \pm 1$.

Thus we have

$$W(\theta) \propto \sum_{m_B} \sum_{m_c} \sum_{m_A} G(m_A, m_B)\, G(m_B, m_c)\, S_{L_2}^{M_2}(\theta) \qquad \text{(equation 4)}$$

In simple cases $W(\theta)$ can be evaluated fairly easily using equation four and taking the Clebsch-Gordon coefficients from tables (Ref. 5).

A more useful and convenient form of the directional correlation function has been developed from a more elegant theory which makes no special choice of the Z axis and is much more general than that presented above. The result of the general theory as given by Biedenharn

and Rose (Ref. 6) is

$$W(\theta) = \sum_{\nu=0}^{\nu_{max}} A_\nu \, P_\nu(\cos\theta)$$

$$\nu_{max} = \min(2I_B, 2L_1, 2L_2) \quad , \quad A_\nu = F_\nu(L_1 I_A I_B)\, F_\nu(L_2 I_C I_B)$$

(equation 5)

The $F(L_i I_j I_B)$ are equal to one for $\nu = 0$. They are tabulated in references 3 and 6 for values of ν greater than zero.

Thus far we have assumed that both transitions are pure. That is, each transition has been considered to consist exclusively of radiation of a single multipole order. However in a great number of cases either one or both of the transitions are mixed. Nuclei may emit in a given transition $I_A \rightarrow I_B$ radiation of multipole order $L' > |I_A - I_B|$ as well as $L = |I_A - I_B|$. Usually mixing occurs with $L' = L+1$ due to the much lower transition probabilities for radiations with higher angular momentum. The ratio of the intensity of the L' radiation to the intensity of the L radiation is δ^{-2} where δ is called the mixing ratio. (Ref. 3).

The general directional correlation function for mixed gamma-mixed gamma cascades is given by Rose. (Ref. 7)

$$W(\gamma\gamma, \theta) \propto \sum_{\nu=0}^{\nu_{max}} \left[F_\nu(L_1 I_A I_B) + \delta_1^2 F_\nu(L_1' I_A I_B) + 2\delta_1 F_\nu(L_1 L_1' I_A I_B)\right]$$
$$\times \left[F_\nu(L_2 I_C I_B) + \delta_2^2 F_\nu(L_2' I_C I_B) + 2\delta_2 F_\nu(L_2 L_2' I_C I_B)\right] P_\nu(\cos\theta)$$

(equation 6)

ν_{max} is defined as in equation five. The $F_\nu(L_i L_i' I_j I_B)$ are defined by the equation $F_\nu(L_i L_i' I_j I_B) = (-1)^{I_j - I_B - 1}\left[(2I_B+1)(2L_i+1)(2L_i'+1)\right]^{1/2} G_\nu(L_i L_i' I_j I_B)$ The G_ν are listed in tables in references 3 and 6. Here δ_1 and δ_2 are the mixing ratios for the first and second transitions respectively. Note that if $\delta_1 = \delta_2 = 0$, equation six reduces to equation five.

Appendix II

Conversion Electra-Gamma Directional Correlation Function

Instead of measuring the directional correlation between two successive gamma rays one can measure the correlation function between the gamma rays from one transition of the cascade and the conversion electrons from the other transition. In observing the conversion electrons we are in effect making an indirect observation of the corresponding gamma radiation. Instead of observing a gamma ray directly we observe its effect on the electrons immediately surrounding the nucleus.

The general directional correlation function for mixed conversion electron-mixed gamma cascades $I_A \xrightarrow{e^-} I_B \xrightarrow{\gamma} I_c$ is developed by Biedenharm and Rose. (Ref. 6)

$$W(e^-\gamma,\theta) \propto \sum_{\gamma=0}^{\gamma_{max}} \Big[C(L_1)\, b_\gamma(L_1)\, F_\gamma(L_1 I_A I_B) + \delta_1^2\, C(L_1')\, b_\gamma(L_1')\, F_\gamma(L_1' I_A I_B) + 2\delta_1 \sqrt{C(L_1)\, C(L_1')}\; b(L_1 L_1')\, F_\gamma(L_1 L_1' I_A I_B) \Big] \times \Big[F_\gamma(L_2 I_c I_B) + \delta_2^2 F_\gamma(L_2' I_c I_B) + 2\delta_2 F_\gamma(L_2 L_2' I_c I_B) \Big] P_\gamma(\cos\theta)$$

(equation 7)

$C(L_i)$ is the internal conversion coefficient for the $I_A \xrightarrow{L_i} I_B$ transition. The particle parameters $b(L_i)$ and the mixed conversion particle parameter $b(L_1 L_1')$ are tabulated in references 6 and 8. They are both functions of the nuclear charge Z, the energy of the transition, and L. In addition the $C(L_i)$ and $b(L_i)$ are functions of the parity of the transition.

APPARATUS FOR MEASUREMENT OF ELECTRON-GAMMA DIRECTIONAL CORRELATIONS

by

CURT HASBROOK CHADWICK

B. S., Kansas State University, 1962

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment for the

requirements for the degree

MASTER OF SCIENCE

Department of Physics

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1965

Abstract

Directional correlation measurements are useful in determining certain properties of nuclear energy states.

Apparatus was constructed to measure the directional correlation between conversion electrons and gamma rays. Two detectors are used- a solid state electron detector which is fixed and a NaI(Tl) scintillator crystal gamma ray detector movable about an axis through the radioactive source. The detectors are enclosed in a large vacuum chamber made of 1" thick aluminum plate, lined with lucite to reduce scattering. A large removable plexiglass window is provided for access to the interior of the chamber. The pumping system consists of a Cenco Hyvac 14 fore pump and a liquid nitrogen trap inserted in the vacuum line between the pump and the chamber. A liquid nitrogen trap is also provided in the chamber itself. This trap is essentially a glass Dewar flask from the bottom of which a tube closed at one end protrutes into the chamber. The trap is attached to the chamber by a tapered seal so that it may be removed. After starting the pump it is possible to attain a pressure of one micron in about an hour.

The solid state electron detector is attached to an adjustable brass arm that fastens to the lower end of a Dewar flask identical to the one used as a cold trap except that the lower end terminates in a Kovar metal to glass seal. The detector can thus be cooled by filling the flask with liquid nitrogen or a solution of dry ice in acetone, which is sufficiently cold for the operation of most solid state electron detectors. The consumption of liquid nitrogen for cooling the detector is approximately 120 cc/hr.

If the cold trap for the chamber is replaced by a flask with a Kovar to glass seal on its lower end, a second solid state detector can be

mounted in the chamber so that coincidence experiments using two solid state detectors may be performed.

The scintillation detector is mounted on a carriage which slides on an arm which in turn pivots on a rod. This rod passes through the wall of the chamber so that the arm can be rotated from outside the chamber. An emitter follower is mounted directly on the back of the photomultiplier tube so that capacitance in the wire leads to the outside of the chamber poses no problem. Two scales are provided for determining the angular position of the scintillation detector, one inside the chamber and one outside. The radioactive source is fixed on the end of a lucite rod at the pivot point of the arm.

The alignment of the detectors and the radioactive source proceeds in a straightforward manner. Various adjusting screws and guide markers are provided to this purpose.

Within the chamber there is a movable absorber holder in which standard graded absorbers may be mounted. The holder can be manipulated from outside the chamber.

An effort was made to test the apparatus by trying to duplicate the results of Rao in the measurement of the directional correlation between the 358 Kev gamm ray and the K conversion electrons from the 81 Kev transition of Ba^{133}. Difficulty was experienced with oil condensing on the cold electron detector and with instability in the gain of the emitter follower. These difficulties invalidated the results of the correlation measurements but a spectrum of the conversion electrons in coincidence with the 358 Kev gamma ray of Ba^{133} was taken.

The instability has been corrected and it is thought that the problem of oil condensation can be corrected by using high grade, low-vapor-pressure pump oil and by building a larger, more effective cold trap for the pump.